Measurements of the energy dependence of the analyzing power in pp elastic scattering in the CNI region

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Abstract.
We present new measurements of the analyzing power A_N in proton-proton elastic scattering in the Coulomb-Nuclear Interference region at $\sqrt{s}$=7.7 and 21.7 GeV obtained with the polarized atomic hydrogen jet target at RHIC. These measurements complement our earlier results at $\sqrt{s}$=6.8 and 13.7 GeV confirming the presence of a hadronic helicity flip amplitude contribution in proton-proton elastic scattering at lower energies ($\sqrt{s}$ <8 GeV), while higher energy data ($\sqrt{s}$ >13 GeV) are consistent with no hadronic helicity flip contribution.

1. Introduction

Proton-proton (pp) scattering is one of the most fundamental reactions in particle physics. It's been serving as a basic tool towards understanding the strong interaction. The addition of spin-dependent scattering results probes quantum chromodynamics (QCD), the theory of strong interactions, in new ways.

Proton-proton elastic scattering is described in terms of helicity amplitudes [1], each of them being a sum of hadronic (strong force) and electromagnetic amplitudes. For very forward scattering (the region of 4-momentum transfer $-t \sim 10^{-2} - 10^{-3}$ $(\text{GeV/c})^2$) the electromagnetic contribution to pp scattering, being negligible at larger $-t$, becomes comparable in magnitude to the hadronic contribution. The interference between them generates additional contributions to different observables in pp scattering. This kinematic region is called Coulomb-Nuclear Interference (CNI) region.

In the case of transversely polarized protons, the interference between helicity non-flip amplitudes and helicity flip amplitudes leads to a sizable transverse spin dependent asymmetry A_N in the CNI region. A_N is defined as a left-right asymmetry relative to the vertically polarized beam or target in the pp scattering cross section. The main contribution to A_N comes from the
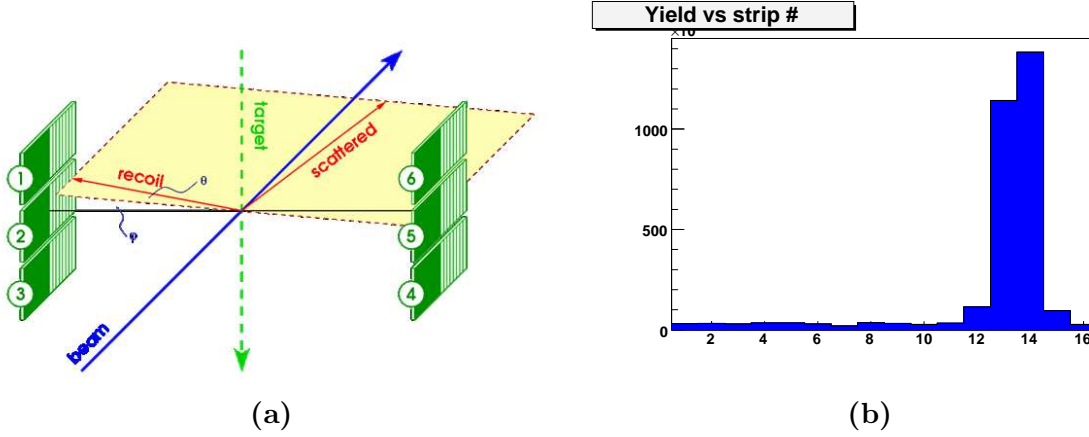
Figure 1. **(a)** H-Jet layout of silicon detectors with strips oriented perpendicular to the beam line; the atomic hydrogen jet goes from the top to the bottom; forward strips are used to measure the recoil proton from the interaction of the jet with one RHIC beam, and backward strips - with the other beam. **(b)** Event distribution for the recoil proton $2.0 < T_R < 2.5$ MeV/c as a function of strip number from the $\sqrt{s}$=21.7 GeV data sample for detector #2, with one beam on the target; for each T_R bin, pp elastic events were selected in "signal" strips centered around the expected θ_R angle (here strips 13-14).

interference between the electromagnetic helicity flip amplitude and the hadronic helicity non-flip amplitude, which is calculable in theory [2]. Another term originating from the interference between the hadronic helicity flip amplitude and the electromagnetic helicity non-flip amplitude can modify the size and the shape of A_N vs $-t$. Therefore a measurement of A_N in the CNI region is a sensitive probe of the hadronic helicity flip amplitude.

In this paper we report the measurements of A_N in the CNI region of $0.002 < -t < 0.008$ $(GeV/c)^2$ with proton beam energies 31 and 250 GeV (corresponding to center of mass energies $\sqrt{s} = 7.7$ and 21.7 GeV), performed using the polarized hydrogen jet target (H-Jet) at RHIC. These data complement our earlier results with beam energies 24 and 100 GeV ($\sqrt{s} = 6.8$ and 13.7 GeV) [3, 4].

2. Experimental set-up

The polarized hydrogen jet target is located at one of the collision points (IP12) in the RHIC accelerator. It consists mainly of three parts: an atomic beam source, a scattering chamber and a Breit-Rabi polarimeter (BRP). Beam source produces the polarized atomic hydrogen jet with a velocity of 1560 ± 20 m/c [5], which intercepts perpendicular with the RHIC proton beam in the scattering chamber. The FWHM of the jet in the center of the scattering chamber is ~ 6.5 mm. The total atomic beam intensity in the scattering chamber was measured to be $(12.4\pm0.2)\cdot10^{16}$ atoms/cm^2 [6]. Along the RHIC beam axis the target thickness is $(1.3\pm0.2)\cdot10^{12}$ atoms/cm^2 [5]. The BRP measures the atomic hydrogen polarization. It is continuously monitored during the run and showed a stable polarization of $P_{target} = 0.958 \pm 0.001$ [5]. The Target polarization is flipped every ~ 10 min to reduce systematic uncertainties in the spin asymmetry measurements.

The recoil protons from the elastic pp scattering are detected using an array of silicon detectors located on the left and right at a distance $\sim$80 cm (Fig. 1a). Three pairs of silicon detectors covered an azimuthal angle of $15°$. The detectors were ~ 400 μm thick, 70×50 mm^2 in size, with 4.4 mm readout pitch for a total of 16 channels (strips) per detector. Recoil protons with kinetic energy up to 7 MeV were fully absorbed. The elastically scattered protons are identified with some contamination of background ($\sim$4–8%) using the kinematical correlation between the recoil proton kinetic energy T_R and its time of flight, as well as its kinetic energy and scattering angle θ_R (selecting "signal" strips as shown in Fig. 1b).
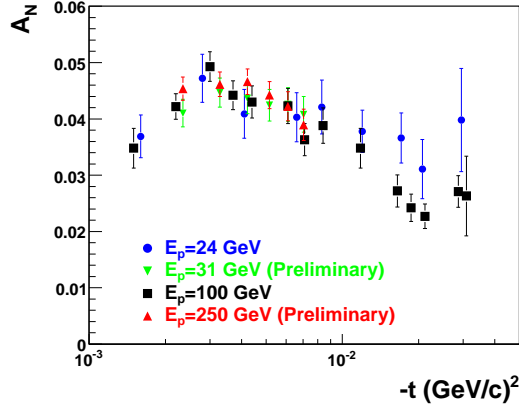
Figure 2. Analyzing power (A_N) for elastic pp scattering; 24 GeV and 100 GeV ($\sqrt{s} = 6.8$ and 13.7 GeV) data are from RHIC Run 2004 ([3] and [4]), 31 GeV and 250 GeV ($\sqrt{s} = 7.7$ and 21.7 GeV) preliminary data are from Run 2006 and 2009, correspondingly; the shown uncertainties are the quadratic sum of the statistical and systematic uncertainties.

The details of H-Jet setup and Data Acquisition system are described elsewhere [3, 4, 7].

3. A_N measurements

The analyzing power (A_N) can be extracted from the asymmetry between the number of scatterings on the left versus on the right, corrected for the left and right detector acceptances, or from from the asymmetry between the number of scattering (e.g. on the left) for target polarization up and target polarization down, corrected for the integrated luminosities for the corresponding target spin states. These two approaches can be combined in so called "sqrt" formula, which cancels contributions from different left-right detector acceptances and different luminosities in the measurements with up and down target polarization states to the asymmetry [8]:

$$A_N = \frac{1}{P_T} \frac{\sqrt{N_L^\uparrow \cdot N_R^\downarrow} - \sqrt{N_R^\uparrow \cdot N_L^\downarrow}}{\sqrt{N_L^\uparrow \cdot N_R^\downarrow} + \sqrt{N_R^\uparrow \cdot N_L^\downarrow}}, \tag{1}$$

where $N_{L(R)}^{\uparrow(\downarrow)}$ is the number of recoil protons selected from pp elastic scattering events detected on the left (right) side of the beam, P_T is target polarization, and the arrows give the direction of the target polarization.

The A_N measurements were performed for the recoil proton kinetic energy range $T_R = 1 - 4$ MeV, corresponding to a momentum transfer $0.002 < -t < 0.008$ (GeV/c)^2 ($-t = 2m_p T_R$, where m_p is the proton mass). The dominant correction applied to the measured asymmetries was due to background, which was evaluated in each T_R bin using the "side" strips (separated from "signal" strips by at least one strip, see Fig. 1b). Interpolated under the "signal" strips, the background contribution varied for the different T_R bins from 4% to 8% and didn't show any spin dependence, hence purely diluted the measured elastic asymmetries by the fraction of the background in the "signal" strips. Another source of a possible dilution of the measured elastic asymmetries is due to background from molecular hydrogen in the atomic hydrogen jet, which can dilute the asymmetries by as much as 3% [5]. At the moment we could not confirm the presence of this background from the recoil proton data, hence we didn't correct for it, but included this possible dilution into the systematic uncertainties.

The total systematic uncertainties of the A_N measurements for the elastic pp scattering was estimated 4–6%, which in addition to the uncertainties due to background included also uncertainties in the recoil proton kinetic energy measurements and variations in the results due to different criteria for the event selection.

Fig. 2 shows our preliminary A_N results for $\sqrt{s} = 7.7$ and 21.7 GeV along with our published
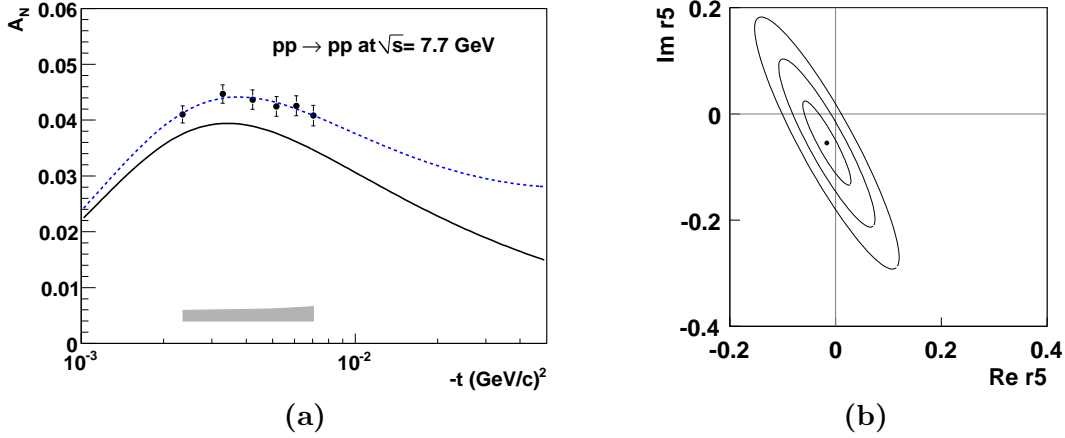
Figure 3. (a) A_N as a function of $-t$ for $pp^{\uparrow} \to pp$ scattering at $\sqrt{s}$=7.7 GeV; the error bars are statistical uncertainties, the lower band represents systematic uncertainties; the solid curve corresponds to the calculation with no hadronic helicity flip contribution; the dashed curve is a fit to the data allowing for a hadronic helicity flip contribution to A_N. (b) r_5 with 1σ, 2σ, and 3σ error contours.

results for $\sqrt{s}$ = 6.8 and 13.7 GeV. The analyzing power near the CNI peak is beam energy independent (within experimental uncertainties).

4. Results and discussion

Fig. 3 and 4 compare the measured A_N data with the calculations having no hadronic helicity flip contribution [1], using the following parameters for the hadronic amplitude description at $\sqrt{s}$=7.7 GeV and 21.7 GeV: total pp cross section σ_{tot}=38.5 mb and 39.3 mb ([9]), real to imaginary ratio of non helicity flip forward hadronic amplitude ρ= -0.20 and -0.02 ([9]), and the exponential slope of the forward hadronic cross section B= 11 $(\text{GeV/c})^2$ and 12 $(\text{GeV/c})^2$. The variation of the calculations due to uncertainties in these parameters (< 0.001) is considerably smaller than our experimental uncertainties in all $-t$ bins [10].

The A_N data were also fitted with calculations allowing for a hadronic helicity flip contribution. The relative hadronic helicity flip amplitude r_5 defined as

$$r_5 = \frac{m_p \, \phi_{flip}^{had}}{\sqrt{-t} \, Im \, \phi_{non-flip}^{had}} \tag{2}$$

is used to quantify this contribution [1], where $\phi_{flip(non-flip)}^{had}$ are helicity flip (non-flip) hadronic amplitudes. Similar to our earlier publications [3, 4], the complex parameter r_5 was extracted from the fit to the data.

The fit results are shown in Fig. 3 and 4 with dashed lines, which correspond to Re r_5= -0.055 (-0.002) and Im r_5= -0.016 (-0.005) for the $\sqrt{s}$=7.7 GeV (21.7 GeV) data samples. The extracted parameters Re r_5 and Im r_5 are correlated, therefore error contours corresponding to 1σ, 2σ and 3σ are shown. The dominant contribution to the uncertainties comes from the systematic uncertainties in the A_N measurements. The correlation between systematic uncertainties in different T_R (or $-t$) bins are propagated to the error contours in Fig. 3b and 4b.

The A_N data at $\sqrt{s}$=21.7 GeV are consistent with no hadronic helicity flip amplitude contribution within experimental 1σ uncertainty, while the $\sqrt{s}$=7.7 GeV data require the presence of a hadronic helicity flip amplitude contribution at a 90% confidence level ($\sim 2.5\sigma$).
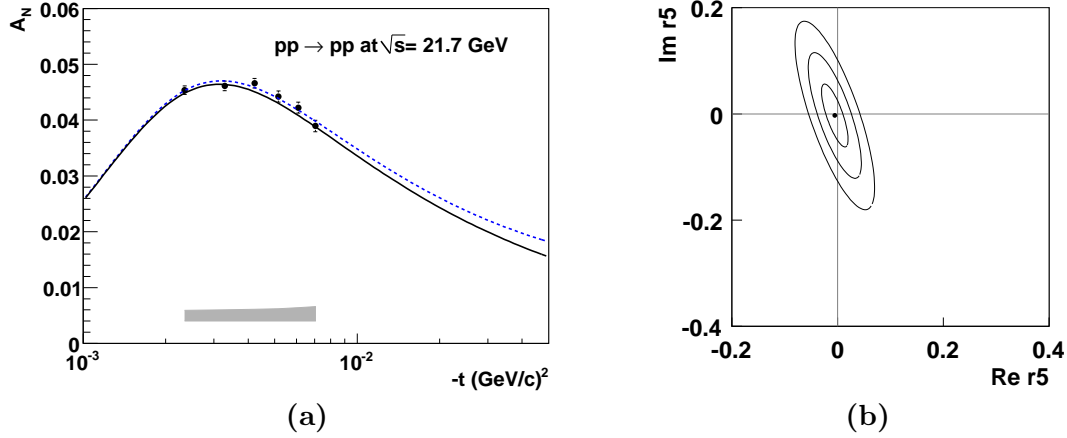
Figure 4. The same as Fig. 3 but for $\sqrt{s}$=21.7 GeV.

5. Summary

The H-Jet target setup serving as an absolute polarimeter for proton beams at RHIC, continues providing precise data on elastic pp scattering in the CNI region with different beam energies. The A_N measurements at $\sqrt{s}$=7.7 and 21.7 GeV presented in this paper along with our published results at $\sqrt{s}$=6.8 and 13.7 GeV indicate on the presence of hadronic helicity flip contribution at low energies, below $\sqrt{s} \sim 8$ GeV. Our higher energy data (at $\sqrt{s}$=13.7 and 21.7 GeV) along with E704 data at $\sqrt{s}$=19.4 GeV [11] and pp2pp data at $\sqrt{s}$=200 GeV [12] are consistent with no hadronic helicity flip amplitude contribution.

The precision of our data is now limited by the systematic uncertainties in A_N measurements. In future RHIC runs we plan to improve the precision of the results by performing the dedicated measurements of the different sources of the background, which are now the main contributors to our systematic uncertainties. We also plan to upgrade our detectors, to improve the recoil proton energy measurements, and to extend the acceptance ($-t$ coverage) of our measurements.

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